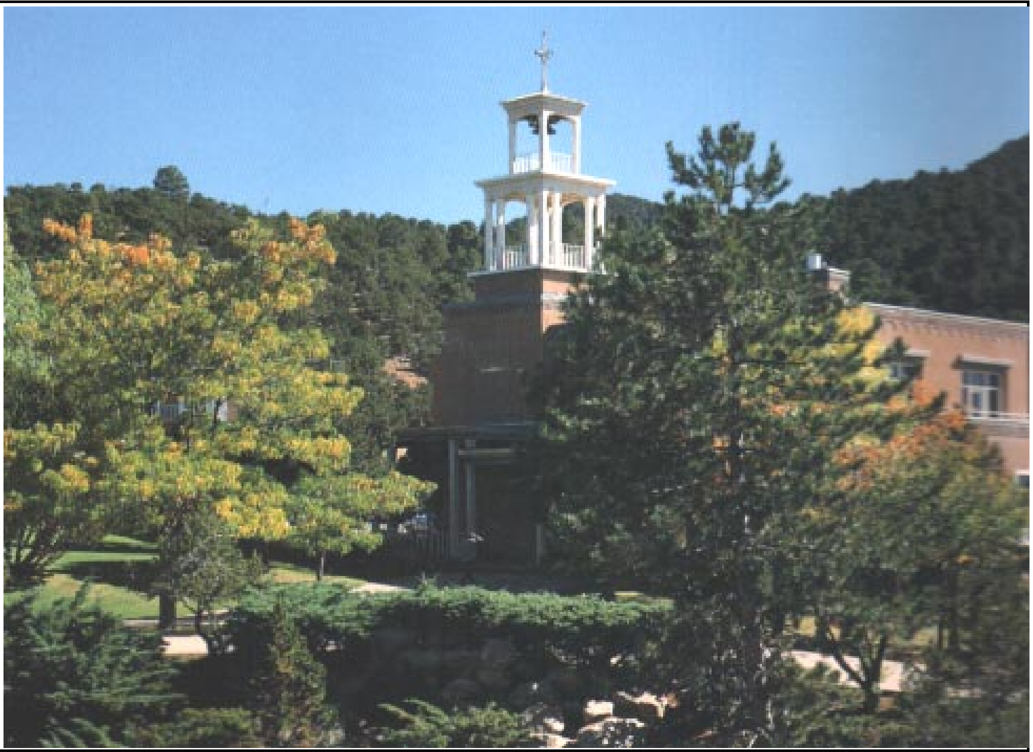
The IRM Quarterly
Summer 1998, Vol. 8, No. 2 Institute for Rock Magnetism



St. John's College was the picturesque venue for the fourth biennial Santa Fe Conference on Rock Magnetism

Santa Fe IV

The Geodynamo and Environmental Change: Interpreting Paleorecords through Rock Magnetism

Mike Jackson
IRM

37 participants from around the world convened for the 4th Santa Fe Conference on Rock Magnetism at St John's College, June 25-28. NSF funding included contributions from both the Division of Earth Science (Geophysics, Geology-ESH, and Instruments and Facilities programs) and the Division of Atmospheric Sciences (Paleoclimate program).

A time-honored maxim of the geosciences is Hutton's "the present is the key to the past," *i.e.*, careful observation of natural processes on the modern Earth provides the best means for interpreting the geologic record. Equally uniformitarian is the reciprocal notion that the past is the key to the present: the geologic record provides us with the best means of understanding certain processes occurring on the modern earth, that are not directly observable due to the spatial and/or temporal scales involved. Two marquee examples are generation of the geomagnetic field in the inaccessible deep interior of the planet, and global climate and environmental change over millennial time scales. Participants in the fourth Santa Fe conference met to discuss progress and problems in gathering and interpreting the magnetic evidence left behind by the action of these processes in the past, and in using their past behavior to better understand their present and possible future operation.

Thematic keynote addresses by **Gary Glatzmaier** (Los Alamos National Lab) and **Frank Oldfield** (PAGES) set the stage for discussion-oriented sessions on (paleo)magnetic field behavior and paleoclimate/paleoenvironmental variations, and their magnetic records. An additional technical session focused on problems and opportunities in analysis of long-core magnetometer data and low-temperature magnetic measurements. Each of the sessions was conducted in the traditional Santa Fe format, with a few provocative lead talks followed by an extended period of open, in-depth discussion.

Paleofield Fluctuations and Paleomagnetic Records

Rapid recent advances in numerical modeling of the geodynamo have led to increasingly meaningful comparisons between modeled behavior and that of the real dynamo, as reconstructed from paleomagnetic studies of reversal frequency, paleosecular variation, transitional field geometries and paleointensity. **Gary Glatzmaier** showed how his model (developed in collaboration with Paul Roberts) responds to different sets of thermal boundary conditions at the top of the core. Zonal heat flux geometries can either enhance or suppress secular variation and reversal frequency, and non-zonal boundary conditions may influence transitional field geometries. The massive amount of data resulting from the simulations is being subjected to the same sort of analysis used in paleomagnetic studies, in collaboration with Rob Coe and **Lionel Hongre**, who presented VGP density maps and other familiar representations of modeled field behavior. **Catherine Johnson** showed through statistical field modeling that traditional descriptive parameters such as VGP dispersion as a function of latitude are relatively insensitive to non-zonal structure, and that other parameters such as inclination variance are better at capturing that aspect of the paleofield.

In the session organized by **Carlo Laj**, dealing with paleosecular variation and paleointensity records for the real geomagnetic field, directional records were discussed by **Laurie Brown** (lavas) and **Steve Lund** (sediments). For the latter, enormous volumes of new data have become available through automated u-channel measurements, which have also provided a new set of technical challenges related to resolution and signal smoothing (as discussed in more detail during the final session). Steve argued that fourteen Brunhes-aged excursions identified in ODP Leg 172 Blake-Bahama sediments represent true paleofield behavior, not measurement artifacts. **Jim Channell** assessed the state of sedimentary paleointensity records, drawing on his recent North Atlantic results, which do not display the asymmetric sawtooth pattern observed elsewhere. Paleointensity records are becoming increasingly important for recognition of paleofield excursions, and the Icelandic sediments

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Visiting Fellows' Reports

The Santa Fe conference took place in the midst of a busy schedule of spring and summer Visiting Fellows at *IRM*. **Chuanlun Zhang** brought a set of thermophilic bacterial cultures for magnetic and Mössbauer analysis. The process of extracellular magnetite production by these bacteria was investigated by characterizing the concentration and size distribution in cultures frozen after differnt incubation times. Serpentinized peridotites from the Iberian continental margin brought **Xixi Zhao**, whose detailed variable-temperature studies shed light on the carriers and origin of the natural remanence. **Doug Elmore** continued his long-term investigation of secondary magnetite produced by a variety of processes including clay diagenesis, organic maturation, and pedogenesis.

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Magnetite produced by thermophilic bacteria

Biogenic magnetite is recognized as a potential source for sediment magnetization. Previous studies have focused on magnetotactic bacteria and mesophilic dissimilatory iron-reducing bacteria. Recently, we have obtained thermophilic dissimilatory iron-reducing bacteria from the deep subsurface. TEM studies of a thermophilic bacterial strain TOR39, obtained from the Taylorsville basin in Virginia, showed magnetite particles ranging from <30 nm to ~130 nm.

Thermophilic iron-reducing bacteria may play an important role in sediment magnetization in thermic environments. However, the magnetic properties of biogenic magnetite formed by thermophiles have not been reported. The objective of my visit to the IRM was to characterize the iron minerals formed by TOR39 under laboratory conditions. I will use the results to determine the kinetics of bacterial mineral formation.

Biogenic magnetite samples were prepared at Oak Ridge National Laboratory. TOR39, acetate, and amorphous iron were incubated at 65°C, and samples were collected at selected time intervals for 90 days. Samples were then brought to the IRM for magnetic analysis. Magnetic susceptibility (χ) was measured on a Bartington bridge; low-temperature (20K) zero-field-cooled (ZFC) and field-cooled (FC) magnetic remanence on the MPMS, and room-temperature hysteresis loops and remanent coercivity on the MicroVSM. A total of 12 samples were analyzed. Mössbauer analysis was also performed on selected samples to determine the oxidation states and iron mineral species formed by the bacterium.

Magnetic susceptibility of biogenic magnetite increased three orders of magnetite after three months of incubation. Measurements on the MPMS and MicroVSM indicated that the increase in magnetic susceptibility was probably due to increases in both the amount of magnetite particles produced and their grain sizes. Estimates from hysteresis loops showed that magnetite concentrations increased from <1% (wt) of the solid material after 9 h of incubation to greater than 45% after 90 d of incubation. Results of ZFC and FC, as well as hysteresis loops, showed an increase in magnetic remanence with increasing incubation time, suggesting an increase in magnetite grain size to stable single domain (SSD) size. Further analysis showed that the volume fractions of SSD particles could be as high as 26% of the total magnetite formed by TOR39, consistent with TEM observations. These particles are significantly different from those formed by mesophilic iron-reducing bacterium GS-15, but can be similar to magnetite particles segregated from magnetotactic bacterial membranes. Results of this study will have important implications for determining the origin of biogenic magnetite in natural environments.

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Rock Magnetic Studies of the Iberian Peridotites

The main objective of my recent visit to the IRM was to investigate the magnetic carriers in the Iberian peridotites and to search for clues to the age of peridotite emplacement and subsequent alteration that accompanied continental breakup and onset of steady-state seafloor spreading in the North Atlantic.

During Ocean Drilling Program (ODP) Legs 149 and 173, which were designed to investigate the nature of the basement within the ocean-continent transition zone in the Iberia Abyssal Plain, off the west coast of Portugal, we discovered a wide region of serpentinized peridotites (upper mantle rocks) that were unroofed in the continental breakup zone. The upper part of the peridotite section immediately underlying the Pleistocene to Lower Cretaceous sedimentary cover is a zone of alteration in which rocks are pervasively veined and brown-colored. The lower part of the section consists of "fresher" greenish-gray serpentinized peridotites. The natural remanent magnetization (NRM) intensities tend to become stronger in the lower part of the peridotite section.

Prior to my visit I characterized the stable components of NRM through detailed thermal and AF demagnetization. In the "fresher" lower part of the section the remanence is dominated by a single component, although several samples did display a dual-polarity multicomponent nature. In the "altered" upper part of the section, the remanence is dominated by a single stable component of normal polarity. Nearly identical directions of this component are found in all samples regardless of lithology and depth. The inclinations of the characteristic remanent magnetization (ChRM) in the "fresher" lower part of the peridotite section show a predominantly reversed polarity in a depth zone of about 21 m. The mean inclinations are significantly shallower than that of present day field (~64°) at the drilling sites, but are similar to those calculated from Cretaceous reference paleopoles for Iberia.

The most exciting and unexpected result of the paleomagnetic study is the identification of magnetic polarity zones, offering promise for dating the tectonic processes that accompanied continental breakup. During my 10 days venture at the IRM, I concentrated my efforts on the following two questions:
(1) Is the polarity sequence primary and can it be used to date emplacement? The reversed polarity of ChRM in the "fresher" lower part of the peridotite section is confined within a depth zone of 21 m. Moreover, this reversed

Visiting Fellow Reports
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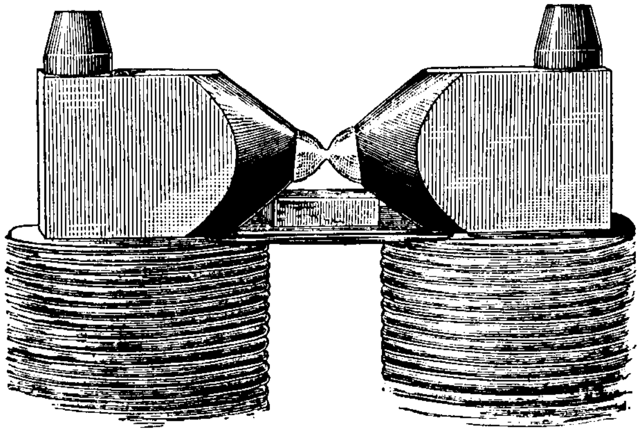

Magnetic Attraction of Liquid Oxygen.

10th December, 1891. "At 3 p.m. this afternoon I placed a quantity of liquid oxygen... between the poles of the historic Faraday magnet, in a cup-shaped piece of rock salt... and to my surprise I witnessed the liquid oxygen, as soon as the magnet was stimulated, suddenly leap up to the poles and remain there permanently attached until it evaporated. To see liquid oxygen suddenly attracted by the magnet is a very beautiful confirmation of our knowledge of the properties of gaseous oxygen." Dewar estimated the magnetic susceptibility of liquid oxygen to be 228x10^{-6} cgs (approximately 3x10^{-3} SI) [The Collected Papers of Sir James Dewar, Cambridge University Press, 1927, p. 334-339, 504-515.]

Current Abstracts

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. *Articles published in familiar geology and geophysics journals are included; special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most abstracts are culled from* INSPEC *(© Institution of Electrical Engineers),* Geophysical Abstracts in Press *(© American Geophysical Union), and* The Earth and Planetary Express *(© Elsevier Science Publishers, B.V.), after which they are subjected to Procrustean editing and condensation for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the* IRM. *This list, with more than 4600 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the* IRM Quarterly *are always welcome.*

Anisotropy

W. D. MacDonald, H. C. Palmer and A. Hayatsu, 1998, **Structural rotation and volcanic source implications of magnetic data from Eocene volcanic rocks, SW Idaho**: *Earth and Planetary Science Letters, v. 156*, p. 225-37.
A clockwise tectonic rotation of about 34° is paleomagnetically inferred for the interval 40 to 15 Ma, accompanying Basin-and-Range regional extension. The maximum susceptibility axes, after correcting for the rotation, indicate a flow source along a trend N55° E-S55° W. A source region northeast of the study area, in the main region of development of the Challis volcanic field, is consistent with these results.

R. J. Varga, J. S. Gee, H. Staudigel and L. Tauxe, 1998, **Dike surface lineations as magma flow indicators within the sheeted dike complex of the Troodos Ophiolite, Cyprus**: *Journal of Geophysical Research, v. 103*, p. 5241-56.
Mesoscopic-scale surface features of dikes are correlated to internal flow within the dikes by comparison with the three-dimensional distribution of elongated phenocrysts near dike margins and with anisotropy of magnetic susceptibility. Flow lineations, restored to their paleoridge orientations, reveal a range of emplacement directions for dikes in the Troodos ophiolite with no preference for vertical over horizontal flow.

Biogeomagnetism

A. S. Bahaj, P. A. B. James and F. D. Moeschler, 1998, **A comparative study of the magnetic separation characteristics of magnetotactic and sulphate reducing bacteria**: *Journal of Applied Physics, v. 83*, p. 6444-6.
Microbial biomineralization of iron results in a biomass which can be separated from water systems by the application of a magnetic field. The affinity of magnetotactic and sulphate-reducing bacteria to heavy metal or organic material accumulation render them useful for the removal of pollutants from waste water. This article reports on the magnetic separation of biomass containing microbial iron oxide (Fe_3O_4, present within magnetotactic bacteria) and iron sulphide ($Fe_{1-X}S$, precipitated extracellularly by sulphate reducing bacteria) in a single wire cell.

Diagenesis, Alteration & Remagnetization

M. Torii, 1997, **Low-temperature oxidation and subsequent downcore dissolution of magnetite in deep-sea sediments, ODP Leg 161 (Western Mediterranean)**: *Journal of Geomagnetism and Geoelectricity, v. 49*, p. 1233-45.
Low-temperature experiments document changes in magnetic mineralogy in Pleistocene hemipelagic sediments at ODP Holes 976D and 977A. The Verwey transition was observed only for samples below 1.3 mbsf. Primary magnetite is interpreted to be covered with a maghemite skin as a result of in situ low-temperature oxidation on the sea floor. The oxidized maghemite skin gradually dissolves with depth, and the Verwey transition is observed below 1.3 mbsf. This depth matches the iron redox boundary inferred on the basis of a sediment color change from tan to green.

J. P. Valet, T. Kidane, V. Soler, J. Brassart, V. Courtillot and L. Meynadier, 1998, **Remagnetization in lava flows recording pretransitional directions**: *Journal of Geophysical Research, v. 103*, p. 9755-75.
Rock magnetic studies, microscopic observations, microprobe analyses and remagnetization experiments have been carried out to investigate the origin of high unblocking-temperature overprints. The most plausible scenario is that baking by the overlying flows was accompanied by low-temperature oxidation of titanomagnetite to cation-deficient titanomagnetite. Similarities with characteristics observed at Steens Mountain suggest that the hypothesis of rapid geomagnetic changes recorded by a single lava flow should be considered with caution.

Paleoclimate and Magnetic Proxy Records

L. V. Benson, S. P. Lund, J. W. Burdett, M. Kashgarian, T. P. Rose, J. P. Smoot and M. Schwartz, 1998, **Correlation of late-Pleistocene lake-level oscillations in Mono Lake, California, with North Atlantic climate events**: *Quaternary Research, v. 49*, p. 1-10.
Sediment ^{18}O values indicate three scales of temporal variation (Dansgaard-Oeschger, Heinrich, and Milankovitch) in the hydrologic balance of Mono Lake between 35400 and 12900 ^{14}C yr B.P. During this interval, Mono Lake experienced four low-stands each lasting from 1000 to 2000 yr. The youngest low-stand, which occurred between 15500 and 14000 ^{14}C yr B.P., was nearly synchronous with a desiccation of Owens Lake, California. Paleomagnetic secular variation data indicate that three of four persistent low-stands occurred at the same times as Heinrich events H1, H2, and H4.

Z. L. Ding, J. M. Sun, S. L. Yang and T. S. Liu, 1998, **Preliminary magnetostratigraphy of a thick eolian red clay-loess sequence at Lingtai, the Chinese Loess Plateau**: *Geophysical Research Letters, v. 25*, p. 1225-8.
Polarity zonation defined by about 680 remanence data yields a basal age of about 7.05 Ma for the section, which represents the oldest wind-blown dust deposited continuously in north-central China during the late Cenozoic. The magnetostratigraphy implies a nearly linear accumulation rate (about 2.98 cm/ka) of atmospheric dust on the Loess Plateau during the period of 7.05 to 2.58 Ma. Comparison of the bulk susceptibility record with the pedogenic characteristics of the red clay observed in the field suggests that magnetic susceptibility in the red clay is not as useful as in the loess-soil sequence to indicate summer monsoon variations.

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D. A. Grimley, L. R. Follmer and E. D. McKay, 1998, **Magnetic susceptibility and mineral zonations controlled by provenance in loess along the Illinois and Central Mississippi River Valleys**: *Quaternary Research, v. 49*, p. 24-36.
Magnetic susceptibility (MS) patterns have proven useful for regional stratigraphic correlations of zones within thick, oxidized Peoria and Roxana silts for more than 350 km. Variations in MS of C horizon loess are controlled by silt-sized magnetite content and are interpreted to reflect changes in sediment provenance. Grain size distributions and scanning electron microscopic observations indicate that MS is not significantly influenced by eolian sorting or diagenetic dissolution. MS and compositional zones may indirectly record a climatic signal, primarily through ice lobe fluctuations in the Upper Mississippi drainage basin.

A. Jelinowska, P. Tucholka, F. Guichard, I. Lefevre, D. Badaut-Trauth, F. Chalie, F. Gasse, N. Tribovillard and A. Desprairies, 1998, **Mineral magnetic study of Late Quaternary South Caspian Sea sediments: palaeoenvironmental implications**: *Geophysical Journal International, v. 133*, p. 499-509.
Varying concentrations of greigite (Fe_3S_4) dominate the magnetic fraction in Late Pleistocene sediments. The synsedimentary formation of greigite indicates that the Late Pleistocene Caspian Sea was brackish or fresh water, poorly ventilated, with water level higher than at the present. The variation in magnetic parameters, with the detrital magnetite-bearing fraction remaining constant, is interpreted in terms of greigite grain-size variation and related to the slight variation in water salinity. Holocene sediments are characterized by detrital magnetite. This indicates better ventilation of the basin and suggests lower water levels than in the Late Pleistocene.

J. L. Loizeau, J. Dominik, T. Luzzi and J. P. Vernet, 1997, **Sediment core correlation and mapping of sediment accumulation rates in Lake Geneva (Switzerland, France) using volume magnetic susceptibility**: *Journal of Great Lakes Research, v. 23*, p. 391-402.
Volume magnetic susceptibility (VMS) profiles are used to correlate 52 cores, with two VMS peaks dated to 1961 and 1943 using time markers (^{137}Cs and Hg contamination) in seven cores. The correlated VMS profiles show a clear decrease in sedimentation after 1961, due principally to the construction of hydroelectric dams on major tributaries of the Rhone River. The estimated sediment deficit of 250,000 t/y is comparable to the mass of sediment trapped in reservoirs located in the watershed.

D. Sun, Z. An, J. Shaw, J. Bloemendal and Y. Sun, 1998, **Magnetostratigraphy and palaeoclimatic significance of Late Tertiary aeolian sequences in the Chinese Loess Plateau**: *Geophysical Journal International, v. 134*, p. 207-12.
Magnetostratigraphic results indicate that aeolian dust accumulation and the related East Asia palaeomonsoon system began at least 7.6 Myr ago, and that the Tibetan Plateau had reached a significant elevation by that time. Late Tertiary palaeoclimatic history is reconstructed on the basis of magnetic susceptibility in the Red Clay. Increases in aeolian dust accumulation for the last 7.6 Myr appear to have a close relation with the uplift processes of the Tibetan Plateau. A remarkable increase of aeolian dust accumulation beginning at 3.2 Ma appears to reflect the influence of an increasing global ice volume on the East Asian monsoon and aeolian dust accumulation.

Paleomagnetic Field Records

D. Gubbins and J. J. Love, 1998, **Preferred VGP paths during geomagnetic polarity reversals: symmetry considerations**: *Geophysical Research Letters, v. 25*, p. 1079-82.
Longitudinal confinement of transitional VGPs can be explained if flux remains concentrated on the same longitudes throughout the transition. The VGP path then depends on site position, reversal sense (R to N or N to R), and sense of flux migration (pole- or equator-ward). Data from the Matuyama-Brunhes reversal are broadly consistent with poleward flux migration.

L. Hongre, G. Hulot and A. Khokhlov, 1998, **An analysis of the geomagnetic field over the past 2000 years**: *Physics of the Earth and Planetary Interiors, v. 106*, p. 311-35.
Using archeomagnetic, sediment and lava data, the authors compute a time-varying spherical harmonic model of the geomagnetic field between 0 and 1700 AD. Statistical analysis of the model confirms an earlier suggestion that the typical time scales involved in in the degree 2 and 3 components are of the order of 150 years. The average nondipole field does not differ significantly from zero. However, a g20 is a likely lasting feature of the magnetic field.

M. Iorio, D. H. Tarling and B. D'Argenio, 1998, **Periodicity of magnetic intensities in magnetic anomaly profiles: the Cretaceous of the Central Pacific**: *Geophysical Journal International, v. 133*, p. 233-44.
Spectral analyses of long magnetic anomaly profiles in the Phoenix and Hawaiian lineations show two to five non-harmonic wavelength peaks. Ratios of four peak wavelengths correlate strongly ($r>0.98$) with the ratios for the Earth's orbital eccentricity periodicities for this time. These observations suggest that the magnetic anomaly signal is influenced by the Earth's changing orbital parameters, probably through their influence on the internal geomagnetic field.

C. L. Johnson and C. G. Constable, 1998, **Persistently anomalous Pacific geomagnetic fields**: *Geophysical Research Letters, v. 25*, p. 1011-14.
A new average geomagnetic field model for the past 3 kyr (ALS3K) helps bridge a large temporal gap between historical models and paleomagnetic studies spanning the last 5 Myr. A quasi-static feature seen historically in the central Pacific has the opposite sign in ALS3K; its structure is similar to, but of larger amplitude than, that in the time-averaged geomagnetic field for the last 5 Myr. Anomalous geomagnetic fields exist beneath the Pacific over timescales ranging from 10^2-10^6 years. This is consistent with seismic observations of the lower mantle.

L. Meynadier, J. P. Valet, Y. Guyodo and C. Richter, 1998, **Saw-toothed variations of relative paleointensity and cumulative viscous remanence: testing the records and the model**: *Journal of Geophysical Research, v. 103*, p. 7095-105.
A recent model [Kok and Tauxe, 1996] attempts to explain asymmetrical sawtooth patterns of relative paleointensity from sediments as the consequence of cumulative long-term viscosity effects. Analysis of the model demonstrates that only a sharp distribution of relaxation times would be able to match the paleomagnetic record, and that unblocking temperatures (T_{ub}) would not exceed 260° C. This is inconsistent with measured T_{ub}. New results including Thellier-Thellier experiments across Brunhes-Matuyama confirm the overall stability of the original records. The sawtooth is unchanged by thermal or AF demagnetization. Thus the "cumulative viscous model" data sets, cannot account for existing saw-toothed paleointensity records.

M. Miki, H. Inokuchi, S. Yamaguchi, J. Matsuda, K. Nagao, N. Isezaki and K. Yaskawa, 1998, **Geomagnetic paleosecular variation in Easter Island, the southeast Pacific**: *Physics of the Earth and Planetary Interiors, v. 106*, p. 93-101.
K-Ar whole rock dating on 13 sites gave ages younger than 0.8 Ma. Reliable paleomagnetic directions were obtained from 34 sites. The VGP angular dispersion was calculated to be 11.8° with an upper and lower limits of 14.1° and 9.8°. The angular dispersion is significantly lower than predicted by theoretical secular variation models. The Pacific dipole window appears to exist also in the southeast Pacific.

T. Saarinen, 1998, **High-resolution palaeosecular variation in northern Europe during the last 3200 years**: *Physics of the Earth and Planetary Interiors, v. 106*, p. 299-309.
Variations in the orientation and relative palaeointensity of Earth's magnetic field during the last 3200 yr have been recorded from a sequence of annually laminated sediments in central Finland. The variations in direction were found to be very similar to records reconstructed from other lakes in Finland and northwest Russia, while the relative palaeointensity curve can be correlated accurately with archaeomagnetic data from Central Europe.

W. W. Sager, C. J. Weiss, M. A. Tivey and H. P. Johnson, 1998, **Geomagnetic polarity reversal model of deep-tow profiles from the Pacific Jurassic Quiet Zone**: *Journal of Geophysical Research, v. 103*, p. 5269-86.
A magnetic polarity reversal timescale, constructed by matching deep-tow anomalies with a rectangular block magnetization model for oceanic crust, covers 11 m.y. (156-167.5 Ma) and contains 88 pre-M29 polarity chrons extending to Chron M41. Because of the inferred periods and magnetization contrasts, we think many of the short-wavelength anomalies represent paleofield intensity fluctuations. Polarity reversals have been documented for the younger part of the timescale covered by our model; thus our data may show a transition from a geomagnetic field behaviour dominated by intensity fluctuations to one dominated by reversals.

T. Sato, H. Kikuchi, M. Nakashizuka and M. Okada, 1998, **Quaternary geomagnetic field intensity: constant periodicity or variable period?**: *Geophysical Research Letters, v. 25*, p. 2221-4.

The relative paleointensity record (NRM normalized by susceptibility) for a sediment core in the Melanesia basin is correlated with previous results from two cores in the same basin, between 0.04 Ma and 1.1 Ma. Variation in SIRM is caused almost solely by variations in $CaCO_3$. A time versus depth correlation has been established from the ^{18}O record. Wavelet analysis shows that major periodicities shift continuously between about 50 ka and 140 ka over time.

T. Williams, N. Thouveny and K. M. Creer, 1998, **A normalised intensity record from Lac du Bouchet: geomagnetic palaeointensity for the last 300 kyr?**: *Earth and Planetary Science Letters, v. 156*, p. 33-46.
Normalisation of the NRM by susceptibility, ARM and SIRM yields relative palaeointensity records that are similar to each other, but not to the normalisor records. However, compacted gyttjas give consistently low palaeointensity values, and high palaeointensities correspond to high SIRM/ARM ratios, which occur during the full glacials of ^{18}O stages 2 and 6 - thus normalisation has incompletely removed lithological and climatic factors from the NRM. To overcome this, we have attempted a secondary normalisation by weighting the palaeointensity values according to a least-squares fit to the SIRM/ARM.

Properties of Magnetic Minerals

R. Dieckmann, 1998, **Point defects and transport in nonstoichiometric oxides: solved and unsolved problems**: *Journal of the Physics and Chemistry of Solids, v. 59*, p. 507-25.
Ideal solution point defect thermodynamics can be applied to the iron oxide magnetite, $Fe_{3-\delta}O_4$. The cation diffusion in this material is also reviewed. Magnetite-based solid solutions are discussed with regard to their defect chemistry and the transport of cations. Finally, two largely ignored topics are addressed: (i) the influence of the valence state of an ion on its diffusivity, and (ii) contributions from near-boundary regions to the variation of the oxygen content of nonstoichiometric oxides.

M. Jackson, B. Moskowitz, J. Rosenbaum and C. Kissel, 1998, **Field-dependence of AC susceptibility in titanomagnetites**: *Earth and Planetary Science Letters, v. 157*, p. 129-39.
AC susceptibility measurements show a strong dependence on field amplitude H_{ac} for a set of synthetic titanomagnetites ($Fe_{3-x}Ti_xO_4$) and for basalts from Hawaii and from Iceland. In-phase susceptibility is constant below fields of about 10-100 A/m, and then increases by as much as a factor of two as H_{ac} is increased to 2000 A/m. Both the initial field-independent susceptibilities and the field-dependence of susceptibility are systematically related to composition. This field dependence can in some cases be mistaken for frequency dependence, and lead to incorrect interpretations of magnetic grain size and composition when titanomagnetite is present.

S. Itoh, O. Inoue and T. Azakami, 1998, **Phase relations and equilibrium oxygen partial pressures in iron-titanium-oxygen system at 1373 K**: *Materials Transactions, JIM, v. 39*, p. 391-8.
Phase relations and the equilibrium oxygen partial pressures in the Fe-Ti-O ternary system at 1373 K have been studied using a thermogravimetric technique in various atmospheres buffered by a CO-CO_2 gas mixture and X-ray diffraction. Both the activities of magnetite and ulvospinel in the Fe_2TiO_4- Fe_3O_4 spinel solid solutions coexisting with metallic iron at 1373 K exhibit negative deviations from Raoult's law.

Y. Kino, F. P. Okamura, K. Yamamoto and K. Siratori, 1998, **An observation of localized 3d electron density distribution of Fe_3O_4**: *Journal of Magnetism and Magnetic Materials, v. 177-181*, p.243-4.
Measurement of X-ray diffraction data was carried out on Fe_3O_4 at room temperature. Data were analyzed using the maximum entropy method. The electron density distribution of the (100) and (110) planes of Fe_3O_4 are examined in detail. Electron density associated with a covalent bond between oxygen and Fe^{3+} ions could be observed at the tetrahedral sites. Furthermore, after subtraction of the core electrons sharp peaks were clearly observed, corresponding to different energy states of the d-orbital of the Fe ions.

X. W. Li, A. Gupta, G. Xiao and G. Q. Gong, 1998, **Transport and magnetic properties of epitaxial and polycrystalline magnetite thin films**: *Journal of Applied Physics, v. 83*, p. 7049-51.
Transport and magnetic studies of Fe_3O_4 films as a function of thickness and morphology suggest that epitaxial strain and growth defects affect the width and temperature of the Verwey transition. In addition, these factors also significantly influence the magnetic coercivity of the films. The low-field magnetoresistance (MR) behaviors of epitaxial and polycrystalline films as a function of temperature were found to be quite similar, suggesting very small contribution to the MR from grain boundaries.

B. M. Moskowitz, M. Jackson and C. Kissel, 1998, **Low-temperature magnetic behavior of titanomagnetites**: *Earth and Planetary Science Letters, v. 157*, p. 141-9.
Low-temperature magnetic properties of multidomain titanomagnetite are markedly influenced by the temperature dependence of intrinsic anisotropy, including the magnetic effects associated with isotropic points for $x<0.4$, rapid temperature changes in the anisotropy constants for $x>0.4$, and electronic and lattice relaxation phenomena over the entire titanomagnetite compositional range. These features produce diagnostic magnetic behavior useful for titanomagnetite identification in natural samples. Moreover, the apparent similarities between the thermal decay of low-temperature remanence of titanomagnetite with pyrrhotite, pure magnetite, and superparamagnetic phases can lead to complications in interpreting low-temperature remanence data when titanomagnetite is present.

C. Peters and R. Thompson, 1998, **Magnetic identification of selected natural iron oxides and sulphides**: *Journal of Magnetism and Magnetic Materials, v. 183*, p. 365-74.
Measurements of initial susceptibility, remanent magnetisations and hysteresis loops have been carried out at room temperature on a range of characterised iron oxides and sulphides in order to attempt qualitative identification of the individual minerals. The minerals studied were magnetite, titanomagnetite, haematite, pyrrhotite and greigite. It was found to be possible to qualitatively identify all the minerals (except titanomagnetites from magnetites) from each other using simple susceptibility and remanence ratios. Using discriminant analysis on both the remanence and hysteresis loop data, it was found to be possible to also distinguish the titanomagnetites from the magnetites purely on the basis of the room-temperature measurements.

H. Stockhausen, 1998, **Some new aspects for the modelling of isothermal remanent magnetization acquisition curves by cumulative log Gaussian functions**: *Geophysical Research Letters, v. 25*, p. 2217-20.
IRM acquisition curves were modelled by cumulative log Gaussian functions to discriminate the different magnetic phases. From the investigation of a magnetite sample it is inferred that the remanence acquisition coercive force for each magnetic component in a sample can be deduced. The method allows detection of minute concentrations of magnetically hard material in a predominant magnetically soft sample and vice versa. It furthermore allows extrapolation of the IRM behaviour of samples that do not reach saturation IRM in the experiment. The study of a natural hematite shows that even well-defined hematite may be contaminated by (ferri)magnetic impurities biasing the remanence acquisition coercive force of the sample towards lower values.

M. Zdujic, C. Jovalekic, L. Karanovic, M. Mitric, D. Poleti and D. Skala, 1998, **Mechanochemical treatment of α-Fe_2O_3 powder in air atmosphere**: *Materials Science & Engineering A, v. A245*, p. 109-17.
Complete transformation of α-Fe_2O_3 to Fe_3O_4 is possible during ball milling in an air atmosphere under appropriate milling conditions as shown by X-ray diffraction analysis, magnetization measurements and differential scanning calorimetry after various milling times. Before nucleation of the Fe_3O_4 phase, the crystallites of the α-Fe_2O_3 phase are reduced to a minimal size accompanied by the introduction of atomic-level strain. It is proposed that the mechanochemical reactions proceed at the moment of impact by a process of energization and freezing of highly localized sites of a short lifetime. Excitation on a time scale of 10^{-5} s corresponds to a temperature rise of the order of $(1-2)*10^3$ K. Decay of the excited state occurs rapidly at a mean cooling rate higher than 10^6 K s^{-1}.

Visiting Fellow Reports

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magnetization zone in the beginning of the "fresher" lower part is correlative among three drilled sites that span more than 40 km. This would argue that the reversely magnetized peridotites were probably the same units and recorded the same geomagnetic field during the time of emplacement. There are still two main issues that are important to consider including (a) the mechanism for acquisition of the ChRM and the possibility of self-reversal, and (b) the ability of peridotites to carry NRM that is stable over geologically significant time intervals.

To rule out self-reversal of NRM, I tried the low-temperature measurements in the MPMS (high-field, 2.5T) and Lakeshore (low-fields, 100-1000 A/m) susceptometers to evaluate downhole variations in magnetic mineralogy. Results show that (titano)magnetites are present in the "fresher" peridotites, with a strong Verwey transition in the vicinity of 110 K, and with field- and frequency-dependent susceptibility curves that resemble those of synthetic TM55 (Jackson, presentation at the Santa Fe 4 Conference, 1998). These results are in excellent agreement with the thermo-magnetic characteristics (done on the high-temperature VSM) where titanomagnetites with Curie tempera-tures around 580°C were identified from the "fresher" peridotites. The hysteresis ratios suggest that the bulk magnetic gain size is in the pseudo-single-domain region but closer to the single domain boundary (e.g., with lower H_{cr}/H_c values). These consistent rock magnetic observations support the hypothesis that the reversely magnetized peridotites in the three drill sites recorded the geomagnetic field during the time of emplacement. The relative larger Koenigsberger ratio and coercivity further suggest that the magnetite is capable of preserving an early remanent magnetization. It now seems to me that the stable remanence in the reversed zone was not due to self-reversal but represented a magnetic memory of the Middle Cretaceous geomagnetic field. Thus, these multiple rock magnetic properties revealed important informa-tion relevant to the relations among magnetic properties and the observed reversal polarity zone, and may allow us to date the emplacement of these peridotites.

(2) Can late-stage alteration be dated with the magnetic overprint?

Because the remanence in the "altered" upper part of the peridotite section is dominated by a single stable component of normal polarity, with nearly identical demagnetization behavior regardless of lithology and depth, this remanence seems best interpreted as an overprint. This interpretation can be refined in light of the new rock magnetic data I obtained at IRM. In contrast to the magnetic properties observed from the "fresher" peridotites, the low-temperature curves for the "altered" peridotites did not show any Verwey transition. Thermo-magnetic analysis using the high-temperature VSM also failed to show evidence for titanomagnetites. The remanent magnetization is carried by a thermally unstable mineral that breaks down at about 420°C, probably maghemite. The field- and frequency-dependent relationships are also directly opposite to those in the reversal zone, with no signs for titanomagnetite characteristics. Although the hysteresis ratios still fall in the pseudo-single-domain region, the cluster is centered towards the multidomain region (with higher H_{cr}/H_c ratios). The values of the Koenigsberger ratio and H_c are also smaller than those of the "fresher" peridotites, indicating the presence of low-coercivity magnetic minerals that carry an unstable remanence and are more susceptible to an external magnetic field. Altogether, these rock magnetic data seem to be sensitive indicators of alteration and support the contention that maghemite is responsible for the magnetic signatures displayed in the altered upper part peridotites. The rock magnetic properties are useful in evaluating the fidelity of the natural magnetic memory in upper mantle rocks and understanding the alteration processes through time.

To sum up, although more basic rock magnetic data are still needed to be able to interpret the remarkable magnetic behavior of the Iberian peridotites, significant progress was already made during my stay at IRM to narrow the possible explanations. Magnetic polarity patterns and rock magnetic properties suggest that the emplacement of the Iberian peridotites probably took place during the Middle Cretaceous (probably at the M0 time, 118 Ma). Because other work shows that alteration was early and because the altered zone still has Cretaceous (shallow) inclinations, the alteration of the upper part of these peridotites probably occurred during the Cretaceous Long Normal Superchron (likely between 117 and 84 Ma) by infiltration of seawater during the opening of the North Atlantic.

The Magnetic Chef

Christoph Geiss
IRM

This is the first installment of a new series covering our favorite restaurants around the lab. We hope that it will give our visitors some ideas where to go between measurements, and we start it off with a long time favorite.

Bona, Vietnamese Restaurant.
rating:☆☆☆☆☆

Bona, on Washington Ave at Oak St. (about five minutes walking distance from the lab), serves all the popular Chinese dishes, such as chicken chow mein, pork chow mein, beef chow mein, shrimp chow mein, special chow mein, chicken fried rice, pork fried rice, beef fried rice, shrimp fried rice, special fried rice ... - you get the idea. But the real treasures are hidden on the last two pages of the menu, called "Vietnamese Tradition," where you can find a variety of noodle bowls and soups. For the adventurous we recommend *Pho Dac Biet Xe Lua*, also known as A1, with a *Three Colors Beans* drink. That's a large bowl of rice stick soup with a variety of interesting beef parts that are not your usual restaurant fare, and a large glass of whitish liquid filled with a substance resembling gummy bears. If you don't feel like crunching through beef tendons and brisket beef, there is plenty of other stuff to choose from. *Pho Tai* is soup with very light cooked slices of beef and vegetables (bean sprouts, mint and whatever else is growing through the mild Minnesota winter) on the side. Other favorite soups include *Mi Bo Vien*, Egg Noodle Soup With Meatballs (with a variety of sauces to dip your meat-balls), and *Bun Rieu*, spicy minced prawn soup with tomatoes. *Bun Ga* is sauteed chicken, served on a salad of bean sprouts, lettuce and cucumber, and cold rice noodles - great food for a hot summer day, and *Bun Tofu* is (yes you guessed right) pretty much the same thing with tofu instead of chicken. *Bun Cha Gio* has egg rolls on the salad. For appetizers you might want to try the *Spring Rolls*, and Vietnamese coffee tops off any meal and saves you a trip to Espresso Royal.

For lunch you should be able to get by with about five or six dollars (that includes the tip and taxes); daily specials cost under 4 bucks. Bona is open every day from 11 AM to 9 PM (Fridays 11 AM to 10 PM), but it gets quite full over lunchtime. Nevertheless the service is superfast and friendly and even if there is a long line you won't wait very long to get a seat. Give it a try during your next visit.

Diagenetic and Pedogenic Magnetite Signatures

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One objective of my visit to the IRM was characterization of chemically-remagnetized rocks to test the hypothesis that the rock magnetic properties of remagnetized rock are distinct from similar rock with primary magnetizations. A detrital magnetization is present in Mesozoic limestones in SE France that have not undergone significant burial diagenesis, and a widespread chemical remanent magnetization (CRM) residing in magnetite is present in rocks where smectite has altered to illite. High quality hysteresis loops were difficult to acquire on the Micromag due to weak magnetizations. Despite this problem, analyses of the loops acquired were sufficient to reach some conclusions. Only a few samples from one remagnetized locality display wasp-waisted loops. On a log/log plot of coercivity ratios versus magnetization ratios samples with a detrital magnetization fall approximately along a line which has previously been described as indicative of primary magnetizations. Chips from remagnetized samples generally fall above the "primary" line but below the line which has previously been interpreted to be characteristic of chemical remagnetization. Low temperature measurements conducted with the MPMS indicate that samples from remagnetized sites have higher amounts of SP magnetite than samples from sites which contain a detrital magnetization. In summary, although there are some differences in the rock magnetic properties in the limestones from France, the differences are subtle and not as pronounced as has been found in some other studies.

To test for the potential influence of chemical processes triggered by a heating event, rock magnetic studies were conducted on Jurassic sediment adjacent to a Tertiary dike in Scotland. Sediment specimens within 85 cm of a 90 cm thick dike contain a Tertiary magnetization with the same direction as the thermal remanent magnetization in the dike, whereas the sediment at greater distances does not carry a stable remanence. Based on IRM acquisition, thermal decay of triaxial IRMs, and S-ratio determinations, magnetite is the dominant magnetic phase in the sediment although hematite is found the dike (< 8 cm). Trends in rock magnetic parameters such as $IRM_{300\ mT}$ and anhysteretic remanence are consistent with an increasing contribution of single domain/pseudosingle domain magnetite towards the dike. Low temperature experiments conducted on the MPMS indicate the presence of abundant superparamagnetic magnetite, and some curves display the Verwey transition. Hysteresis loops were again difficult to acquire from these weakly magnetic samples. Hysteresis loops from most samples greater than 8 cm from the dike close below an applied field of 300 mT, consistent with magnetite being the dominant magnetic mineral. Hysteresis loops of samples less than 8 cm from the dike remain open up to high field strengths and are wasp-waisted, consistent with a mix of hematite and magnetite. Samples from between 85 and 8 cm have higher coercivity ratios than background samples which is consistent with a change in the mix of magnetite grains with contrasting coercivities and could be due to a shift to coarser magnetite. The onset of changes in the magnetite grain-size budget starting at 85 cm or approximately one dike-width suggests that chemical processes contributed to the remanence.

Another objective of my visit was to characterize samples in two upper Paleozoic loess sequences. In a previous *IRM* visit, Bodo Katz acquired low temperature and hysteresis data for paleosols and loess in the Maroon Formation, Colorado, which indicated that susceptibility variations were related to differences in concentration and grain size of magnetite. The results were consistent with formation of SP magnetite during pedogenesis. Investigation of loess and paleosol samples from the lower Cutler beds in Utah indicate that bulk susceptibility is variable and does not follow the same pattern as in the Maroon (high in paleosols, low in loess). Determination of the paramagnetic susceptibility from hysteresis loops indicates that it is relatively high and in some cases is equal to the ferrimagnetic susceptibility. This probably accounts for the variable bulk susceptibility results. The source of the high paramagnetic susceptibility is currently under investigation. The low temperature behavior of the Maroon paleosols and the lower Cutler beds also contrast significantly. Thermal demagnetization of a saturation remanence acquired at 20 K shows the Verwey transition in both units, although it is suppressed in the lower Cutler samples. A significant decrease below 50 K in the remanence for the Maroon samples suggests the presence of significant amounts of superparamagnetic magnetite. A more gradual drop in the curves for the Cutler samples, and the suppression of the Verwey transition, suggest oxidization of magnetite. The reason for these differences, as well as differences in the cooling curves, are currently under investigation by Monika Cogoini.

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continued from p. 1

show evidence of only one excursion during the Brunhes.

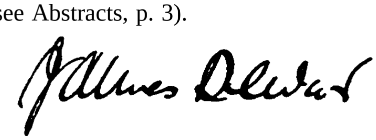
Horst Worm's session on basic rock magnetism and granulometry included an overview from **Wyn Williams** on the state of micromagnetic modeling, which, like dynamo modeling, has flourished by keeping pace with the rapid recent advances in computing capacity. Non-cubic grains, dislocations, and ever-increasing grain sizes have become computationally feasible. **Andy Newell** posed the interesting and important question "from a theroretician's viewpoint, what sort of measurements should experimentalists be making?" and discussed a variety of answers including coercivity variation with grain size and M(H) curves of superparamagnetic assemblages. Low-temperature techniques of mineral identification and granulometry were reviewed by **Subir Banerjee**, who

Santa Fe 4 *continued on p. 8...*

Dewar, Sir James

b. Sept. 20, 1842, Kincardine-on-Forth
d. March 27, 1923, London

Dewar's interest in high- and low-temperature physics and chemistry led him to develop the double-walled and silvered vacuum-insulation vessel for storage of liquified gases, known today as the dewar flask or thermos bottle (essential in modern cryogenic research and for picnics). He was the first to liquify hydrogen and helium, and investigated the electrical and magnetic properties of many materials at low temperature. Among other things, he discovered that liquid oxygen is strongly magnetic (see Abstracts, p. 3).



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emphasized the importance of the continuing trend toward "quantitativity" in data analysis.

Magnetic Signatures of Paleoclimate and Paleoenvironmental Change

A critical mass of empirical data show that magnetic mineralogy responds sensitively to environmental change. **Frank Oldfield** distinguished three roles that magnetic studies can play in the paleoenvironmental research: service (e.g., core correlation); qualitative partnership (e.g., multiproxy studies); and quantitative leadership (e.g., paleoprecipitation proxy in paleosols). In this sequence there is an increasing level of complexity due to the non-uniqueness and model-dependence of the magnetic property-paleoenvironment relationship: many factors conspire to determine magnetic mineralogy and size distribution. Drawing on numerous examples from his research, Frank showed that this complexity can often be turned to advantage: magnetic properties contain information on a great variety of paleoenvironmental conditions and processes.

Two ensuing sessions led by **Rich Reynolds** evaluated the applications and the underlying basis of "proxy" records (both magnetic and nonmagnetic) of paleoenvironmental change. Nonmagnetic properties can often be linked in an unambiguous way with particular natural processes or environmental parameters (*e.g.*, carbonate content with bioproductivity, clay mineralogy with weathering), making them true proxies. **Andy Roberts** assessed the links between magnetic parameters and paleoenvironment, problems with nonuniqueness, and the difficulties in developing true magnetic proxies of paleoenvironmental conditions. **Cor Langereis** offered his views on cyclostratigraphy and marine-continental correlations, pointing out the values of a variety of magnetic, mineralogical, and statistical tools.

The sedimentary-magnetic signatures of human activity were reviewed by **Ken Verosub**, who showed examples both of changes in the balance of natural magnetic inputs (due to human land-use impacts on erosion and drainage) and new influx of anthropogenic magnetic materials. **Rich Reynolds** described the bacterially-mediated formation pathways for magnetic sulfides, offering the view that bacterial sulfate reduction is much more important in forming natural greigite than is intracellular production by magnetotactic bacteria.

The final session, led by **Ken Verosub**, explored ways of effectively handling and critically evaluating the tremendous volumes of data generated by automated u-channel magnetometers. Edge effects and smoothing of sharp variations were discussed, as well as the dependence of various standard magnetic parameters on core translation rate.

The "applied" and "pure" aspects of magnetic paleorecord interpretation continue their mutually-reinforcing parallel development. Multiproxy studies help reconstruct environmental and climate history, and at the same time help us to understand how environmental changes affect magnetic mineralogy and size distribution through depositional and postdepositional processes. Paleosecular variation, paleointensity, and field reversal studies shed light simultaneously on past behavior of the dynamo and on natural mechanisms of magnetic recording and overprinting. Both sorts of study continue to demand and to deliver improved ways of unambiguously linking magnetic measurements to the composition, concentration and size distribution of magnetic minerals.

New IRM Visiting Fellows

We are pleased to announce that seven Visiting Fellowships have been awarded for the period September 1998 - February 1999. Proposals were evaluated by IRM's Review and Advisory Committee (chaired by John King), and the following projects were approved:

Patrick Colgan, *Northeastern University*, Paleomagnetism and rock magnetism of till exposed in Boston Harbor drumlins

Mark Lackie, *Macquarie University*, Rock magnetic studies of a duplicate sample set and some Late Paleozoic New England Orogen ignimbrites

Robert Musgrave, *Latrobe University*, Rock magnetic signature of gas hydrate migration

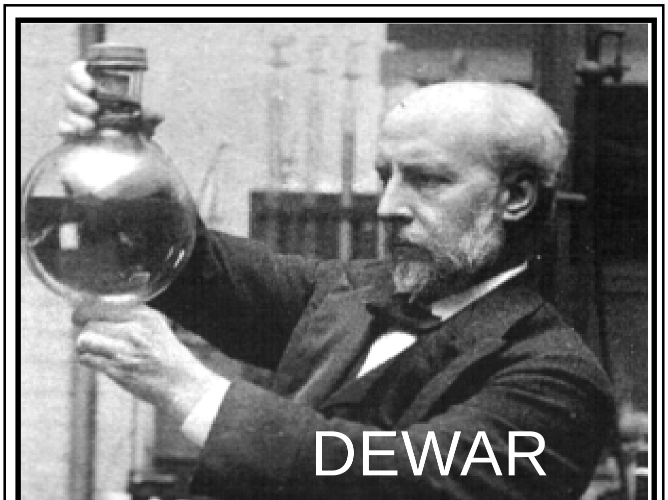
Alexei Smirnov, *University of Rochester*, Low-temperature study of superparamagnetism and bacterial magnetite in pelagic sediments

Jimin Sun, *Institute of Geology, Chinese Academy of Sciences*, Factors affecting magnetic susceptibility of northern China soils

Toshitsugu Yamazaki, *Geological Survey of Japan*, Rock magnetic study of rapidly altering marine sediments

Robert Zergenyi, *ETH Zürich*, Iron mineralogy of recent soils

Collector's Series #10



from *The Collected Papers of Sir James Dewar*, edited by Lady Dewar, 1927, Cambridge University Press

The *Institute for Rock Magnetism* is dedicated to providing state-of-the-art facilities and technical expertise free of charge to any interested researcher who applies and is accepted as a Visiting Fellow. Short proposals are accepted semi-annually in spring and fall for work to be done in a 10-day period during the following half year. Shorter, less formal visits are arranged on an individual basis through the Facilities Manager.

The *IRM* staff consists of **Subir Banerjee**, Professor/Director; **Bruce Moskowitz**, Associate Professor/Associate Director; **Jim Marvin**, Senior Scientist; **Mike Jackson**, Senior Scientist and Facility Manager, and **Peat Solheid**, Scientist.

Funding for the *IRM* is provided by the **W. M. Keck Foundation**, the **National Science Foundation**, and the UofM.

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